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Procedia - Social and Behavioral Sciences 96 (2013) 865 – 872
Procedia
Social and Behavioral Sciences

13th COTA International Conference of Transportation Professionals (CICTP 2013)

Evacuation Route Optimization Based on Tabu Search Algorithm and Hill-Climbing Algorithm

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Abstract

An optimization model for network evacuation route planning is constructed by taking into consideration the strategies of using reverse lane and eliminating intersection conflicts to minimize the total evacuation time in the dangerous areas. The optimization model is a bi-level model. The upper-level is to find optimized sub-network configuration of roadway section with lane reversal by the tabu search algorithm; the lower-level uses the hill-climbing algorithm to get the optimal routing plan with intersection crossing conflicts elimination. In order to prove the validity of the model and algorithm, this paper uses a simple example to illustrate its advantages.The calculation result shows that to solve the problem of evacuation route, the optimization algorithm designed in this paper not only can achieve an excellent computing result, but also has a better computational efficiency, a faster convergence rate and a relatively stable computing result.

Keywords: Lane Reversal; Crossing Elimination; Evacuation Route; Tabu Search; Hill-Climbing

1. Introduction

With the development of social process and the growing damages humans made to the environment, we are facing the threat of a growing number of natural disasters and other catastrophic emergencies. Disasters may be unavoidable, but humans can use advanced technological methods to forecast and warn the disasters before they occur (Tuydes and Ziliaskopoulos, 2006), and make contingency plans. Facing the city's sudden catastrophic events, the most fundamental way is to evacuate traffic rapidly and in time to prevent and reduce casualties.

Domestic and foreign scholars have conducted a relatively in-depth research in the field of emergency evacuation path planning (Urbina and Wolshon, 2003). In many cases, however, most of evacuation delays occur

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doi:10.1016/j.sbspro.2013.08.098

in the intersection. Shinar (1998) found that the traffic evacuation demand is so large that the traffic control measures of both the signal controlled intersections and the non-signal controlled intersections cannot meet it. People's aggressive driving caused by depression and panic in emergency has a bad effect on the intersection control efficiency. Cova and Johnson (2003) fully considered the intersection control, and proposed the replacement evacuation strategy based on lane: eliminating intersection conflicts, which provided an effective and feasible method to reduce intersection delay. Removing intersection traffic control significantly increases the traffic capacity of the intersection. Taking the factors of evacuation time and path complexity into account, Yuan Yuan (2008) built a two-object optimization model and designed an ant colony optimization algorithm to solve it. In the application of the evacuation of the road network optimization model, the effect of using reverse lane and eliminating intersection conflicts together is more obvious than using them respectively. Wang Jian (2010) used Lingo software to compare the evacuation extended network model based on the lane level and the node-arc network model based on road level, and discovered that the evacuation extended network model based on the lane level reduces travel costs and improves the evacuation efficiency.

Focusing on emergency traffic evacuation, this paper reduces intersection delay and total evacuation time by eliminating the intersection conflict points and reducing intertwined quantity. Considering the characteristics of emergency evacuation path, this paper abstracts a mathematical model and utilizes the tabu search algorithm and the idea design algorithms of hill-climbing algorithm to solve the model.

2. Model formulation

2.1. notation and variables

Constructing a directed graph that represents an evacuation network, $G=（N, A）$, where N and A are sets of nodes and links in the graph respectively (Chi Xie, 2011). In the evacuation network, the link A includes the intersection link set A_I and the roadway-section link set A_R where $A=A_I \cup A_R$ The roadway-section and intersection links have different details: the roadway-section links contain capacity, speed, and other attributes, while the intersection links contain traffic flow and turning movements.

Sets and Variables	
N	set of nodes
A	set of links
A_R	set of roadway-section links
A_I	set of intersection links
n_{js}	number of lanes on link (j, s)
c_{js}	capacity of link (j, s)
x_{js}	evacuation flow rate on link (j, s)
t_{js}	travel time on link (j, s)
z_{js}	connectivity indicator of link (j, s)
y_{ij}	connectivity indicator of link (i, j)

The intersection network and the roadway-section network are illustrated in Fig.1. The intersection network includes 8 nodes and 12 links, and the roadway-section network consists of 6 nodes and 4 links. Among the nodes of the roadway-section network, node *s* and *t* are assigned as traffic source nodes. The two indicators y_{ij} and Z_{js} indicates the connections between intersection and roadway-section.

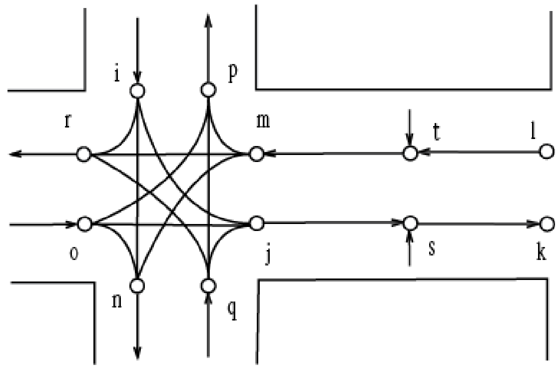


Fig.1 Intersection network and roadway-section network

2.2. Model Formulation

The goal of the model is to eliminate the cross-conflict of intersection and minimize travel costs of all the evacuees. The objective function consists of two parts: the first part is the objective function of the original problem, the total evacuation time; the second part is the penalty term caused by the Lagrangian relaxation method, which indicates the total penalty value of the entire evacuation network.

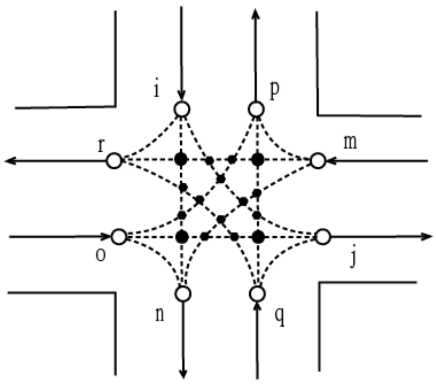


Fig.2 Intersection conflict

It is assumed that four legs of the intersection are bidirectional, and the intersection point of all lanes are regarded as a single lane group, the constraints of eliminating the intersection conflict are as follows. As is illustrated in Figure 2, the steering of all legs is allowed. According to the relative position of the intersection node, the elimination of the conflict points can be expressed as the constraint condition (2). The conflicts between adjacent straight lanes are represented by larger dots, while the conflicts of the left turn lane and two adjacent straight lanes are represented by relatively smaller dots.

$$Z = min\sum_j \sum_s x_{js} t_{js} + \sum P_{ij,mn}\left[\left(y_{mr} + y_{qp} - 1\right) + \left(y_{ij} + y_{mn} + y_{qp} - 1\right)\right] \tag{1}$$

$$y_{mr} + y_{qp} \le 1, y_{ij} + y_{mn} + y_{qp} \le 1, \forall (m,r),(q,p),(i,j),(m,n) \in A_I \tag{2}$$

$$n_{js} = n_{sk} = n_{jk}, n_{lt} = n_{tm} = n_{lm}, \quad \forall (j,s),(s,k),(l,t),(t,m) \in A_R \tag{3a}$$

$$n_{jk} + n_{lm} = n_{jk,mn}, n_{jk}, n_{lm} \ge 0 \quad \forall (j,s),(s,k),(l,t),(t,m) \in A_R \tag{3b}$$

$$z_{js} \le n_{js}, z_{js}M \ge n_{js}, \forall (j,s) \in A_R \tag{4}$$

$$\sum_{n\in\Gamma(m)} y_{mn} = 1, \forall (m,n) \in A_I \tag{5}$$

$$0 \le x_{js} \le c_{js} z_{js}, \forall (j,s) \in A_R \tag{6a}$$

$$0 \le x_{ij} \le c_{ij} y_{ij}, \forall (i,j) \in A_I \tag{6b}$$

The constraint (1) is the goal function.The travel time of link (*j*,*s*) t_{js} adopts Bureau of Public Roads function, which is a function of the link flow rate, x_{js}, and the lane capacity on link (*j*,*s*), c_{js} $t_{js} = t_{js}^0 (1 + \alpha (x_{js}/c_{js})^{\beta})$, t_{js}^0 is the free-flow travel time of link (*j*,*s*); α and β are constants; x_{js} is the flow rate of link (*j*,*s*); c_{js} is the capacity of link (*j*,*s*). And $\left(y_{mr} + y_{qp} - 1\right) + \left(y_{ij} + y_{mn} + y_{qp} - 1\right)$ represents the crossing conflicts number on the network, $P_{ij,mn}$ is a unit penalty cost of violation of the crossing conflicts elimination constraints.

The constraints for the lane reversal operation are as follows: (3a) regulates that numbers of lanes should be the same for consecutive link pair; (3b) represents the relationship between the numbers of lanes of two directions of a roadway section.

. The constraint (4) means that there is an inherent relationship between the road connection targets and the number of lanes. n_{js} and z_{js} follows the logical relationship: if $n_{js} > 0$, then $z_{js} = 1$; if $n_{js} = 0$, then $z_{js} = 0$. *M* is large enough, $M \ge max_{jk,lm} n_{jk,lm}$.

The constraint (5) illustrates that the flow out of the node must be equal to the flow into the node and the uniqueness to flow out for each node.

3. Algorithm design

This paper uses meta-heuristic method to simplify this network optimization problem. This approach uses Lagrangian relaxation method to decompose the problem and reduce complexity. In the framwork of Lagrangian relaxation, eliminating the intersection is realized through the penalty term in the objective function, which means placing the intersection conflict in the objective function as the penalty term. And use tabu search algorithms and hill-climbing algorithm to solve the upper and lower layers respectively.

3.1. Upper-level: Tabu Search Algorithm

Tabu search algorithm is one of local search technology, and it uses memory structure to enhance local search. This approach uses a neighborhood search process to seek from one result to another adjacent one iteratively until a termination criterion is met.

Step 1: Confirm parameters of the initial network, which contains initial network flow, direction and number of lanes. Define tabu tenure and maximum iteration number. Set iteration t=0. Create empty lists: tabu list, search list. Based on the hill-climbing algorithm of lower-level, determine the connectivity of each intersection connector in the base case, and acquire the system travel time F(0) on the initial network.

Step 2: Neighborhood candidate moves can be defined as the increase, decrease or conversion of connections, and lane exchange of the connected group in the opposite direction. Iterations t=t+1, determine the search list. If the two directions of the roadway section are connected, calculate the values of $g_{jk}=(x_{js}/c_{js})^{\beta+1}+(x_{sk}/c_{sk})^{\beta+1}$ and $g_{lm}=(x_{lt}/c_{lt})^{\beta+1}+(x_{tm}/c_{tm})^{\beta+1}$ based on the various each link flow; if $g_{jk}<g_{lm}$, then add the link (*j*, *k*) into the search list. If the link (*j*, *k*) does not belongs to the tabu list, one lane of the link (*j*, *k*) is reversed.

Step 3: Computing current optimal sub-network of intersections based on the lower-level algorithm under certain lane reversal configuration in the iteration *t*. Record the objective function value as *Z*(*t*). If *Z*(*t*)<*Z*(*t*-1), the move is accept.

Step 4: If the candidate move is opposite to the move of the tabu list, then the move is marked as tabu ,and its candidacy is canceled unless it meets the aspiration criterion. Put the link (*l*, *m*) that gains a lane into the tabu list which is not allowed reversing the lane of the link and losing capacity until the number of iterations reaches a predefined tabu tenure, record the evacuation network w_t at this time and the system objective function *Z*(*t*).

Stopping rules: When either the search list is empty and improved searches options have been tested to be ineffective to improve the objective function, or iteration number reaches the maximum iteration number, the search can be terminated.

3.2. Lower-level: Hill-climbing Algorithm

Hill-climbing algorithm has strong local search performance. It starts from any initialized group, in order to get a better search area, it iterates from generation to generation, until it reaches the optimal solution(He Junliang, 2007).

Step 1: Determine the maximum iteration number, unit penalty cost of infeasible path, hill-climbing probability P_{hc}.

Step 2: Set the number of iterations W=0, and generate n individuals (chromosome or feasible solution) to comprise the initial solution S(0) randomly.

Step 3: Calculate the hill-climbing probability P_{hc} of each iteration, $P_{hc}(\mathrm{w})=p_0e^{-\alpha(1-\mathrm{w}/\mathrm{W})}$. Forming a new result, which is denoted as *S*(w). In order to maintain the diversity, searching for few individuals locally in the early stages of evolution; When the population evolution to the late, individuals in the population have been close to the global optimal solution, the greater probability of local search will allow the algorithm accelerate convergence to the global optimal solution(Lang Maoxiang, 2002).

Step 4: Neighborhood can be defined as two exchange process. Exchanging the neighborhood, and forming another result NewS(w), if NewS(w)<S(w), then S(w)=NewS(w).

Stopping rules: the number of generations meets requirements.

4. Illustrative example and Result analysis

A simple example originated from the article of Xie and Turnquist (2011) is demonstrated to show advantages of the proposed model. The network topology is shown in Figure 3. All of the turning movements are alternative at intersection 2.

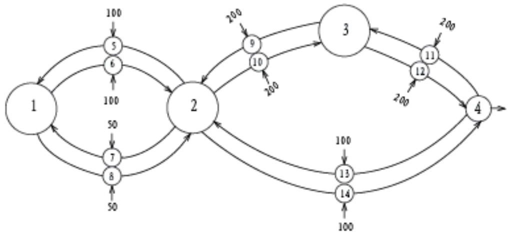


Fig.3 road network layout

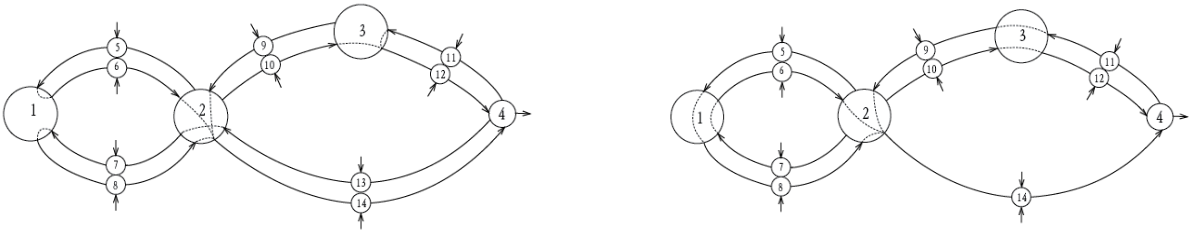
And parameters, like free-flow travel time, capacity, number of lanes, are indicated in Table 1.

Table 1. parameters of each link pair

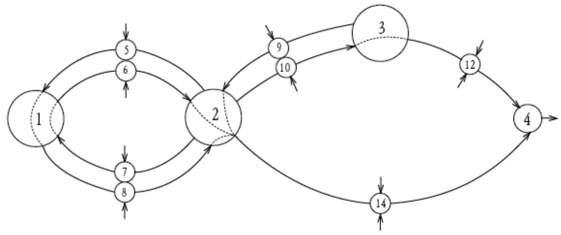
Arc pair	Free-flow travel time	Capacity	Number of lanes
1-6-2	5	100	1
2-5-1	5	100	1
1-8-2	5	100	1
2-7-1	5	100	1
2-10-3	5	200	1
3-9-2	5	200	1
3-12-4	5	150	1
4-11-3	5	150	1
2-14-4	10	200	1
4-13-2	10	200	1

Algorithmic parameters in the upper-level include tabu tenure=3, the maximum iteration number=10; while parameters in the lower-level include the unit penalty cost=1×10^4 time units;W=30, p_0 =0.1, α =1；

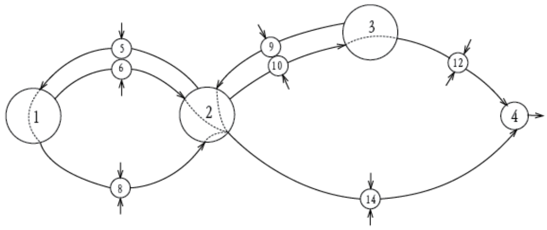
The integrated search procedure is depicted in Fig.4. Each iteration solution shows the lane-reversal configuration and the optimization routing under the roadway section sub-network. The objective function values of each iteration solution are also represented in the figure.



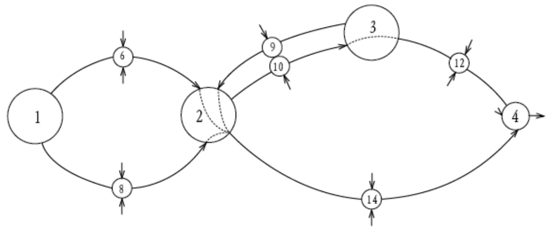
(a) Iteration 0 ($Z=3.947\times10^5+2\times10^4$) (b) Iteration 1 (Z=9.396×104+0×104)



(c) Iteration 2 (Z=4.150×104+0×104)



(d) Iteration 3 (Z=4.001×104+0×104)



Iteration 4 (Z=3.886×104+0×104)

Fig.4 Iterative solutions of the illustrative example

Since there is a relatively clear destination, the reverse lane is extensively used. As is depicted in Fig.4(e) , most lanes are one-way traffic, which greatly enhancing the capacity. Compared with the best solution of Xie and Turnquist (2011) in figure 5, there are some differences between the two solutions: in our solution, the total travel time reduces by 24%;and the intersection point of conflict turns to zero after the first iteration, while it is the fifth iteration in Xie and Turnquist(2011). Therefore, the model in this study is much more efficient.

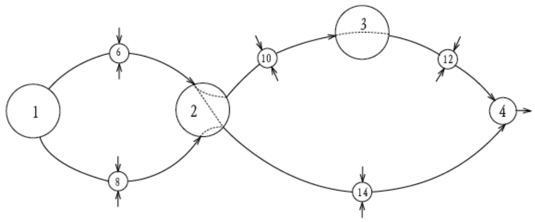


Fig.5 Comparative case solution results

5. Conclusion

In this paper, we construct an optimization model for network evacuation contraflow and route planning with intersection crossing conflicts elimination strategies that minimizes the total evacuation time in the dangerous area. The proposed optimization model is a bi-level model based on the system optimal allocation method. Such evacuation plan can be used as contingency plans for the long-term planning, and it can also be used as the real-time management system initial plan to improve the efficiency of the real-time management.

Looking forward into the future, we still need to further consider the effect of evacuation efficiency caused by a different trip mode or different evacuation traffic load. Once there are uncertainties, such as the road network facilities have bottleneck, the algorithm validity also need to be improved to be adapt to the application needs of the larger-scale road network.

6. Copyright

Acknowledgements

This research is supported by the National Natural Science Foundation of China (No. 51078086). The authors appreciate the Jiangsu Provincial Key Laboratory of Transportation Planning and Management of Southeast University.

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